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TP 9647E

Modeling of Ice Class Shafting and Propeller Systems

Final Report

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Prepared for

Transportation Development Centre
Policy and Coordination Group
Transport Canada

by

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Language Notice

Un sommaire en français de ce document est inclus avant la table des matières.

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This program has been conducted with the support of the Transportation Development Centre of Transport Canada, an Agency of the Canadian Federal Government located in Montreal, Quebec.

Fleet Technology Limited acted as the principal contractor to the project with overall responsibility for the software design, the development of the modeling technique, the collation of the full scale data, and the subsequent analysis and reporting of the results.

The following subcontractors were commissioned by Fleet Technology Limited:

Arctic Research and Development Ltd.
Assisted with certain aspects of the ice-propeller interaction equations.

Mr. Mike Smyth , a graduate student at the University of Calgary
Assisted with the development of the software for the dynamic response calculation of the torque, thrust, and alignment models.

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16. Abstract

A number of successful full-scale tests of icebreaker propulsion systems have been completed in recent years. The principal motivation for much of this work has been to provide an adequate experimental basis for the development and validation of numerical modeling techniques for predicting the performance of alternative shafting and bearing arrangements. The objective of this project was to develop a software package to access the full-scale data and execute numerical models, for the design and evaluation of ice class shafting and propeller systems. The software package developed, the Shaft Modeling Tool Kit, is written for IBM PC/AT compatibles and provides:

- Access to key full scale data from several ice class vessels;
- Tabular displays of the Canadian Arctic Shipping Pollution Prevention Regulations for powering, shafting, and propellers;
- Analytical modeling of generalized shafting and propeller systems for torsion, thrust, and alignment (Dynamic and Static).

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16. Résumé

Un certain nombre d'essais concluants en vraie grandeur, réalisés ces dernières années, ont permis de caractériser le comportement des systèmes propulsifs des brise-glace. Ces essais avaient été principalement entrepris dans le but de constituer une base expérimentale solide pour l'élaboration et la validation de techniques de modélisation numérique visant la simulation du comportement de diverses configurations de lignes d'arbres de propulsion. L'objectif de ce projet a été de mettre au point un progiciel de traitement des données en vraie grandeur pour l'élaboration de modèles numériques devant servir à l'étude et à l'évaluation de systèmes propulsifs (arbre et hélices) renforcés pour la navigation dans les glaces. Le progiciel en question, appelé "Shaft Modeling Tool Kit" et fonctionnant sur ordinateurs IBM PC/AT compatibles, offre les fonctions suivantes:

- Traitement des données en vraie grandeur concernant plusieurs navires de cote arctique pour en extraire les paramètres clé.
- Affichage sous forme de tableau des valeurs spécifiées dans le Règlement sur la prévention de la pollution des eaux arctiques par les navires, à l'égard des systèmes propulsifs (machines, ligne d'arbre et hélices).
- Modélisation analytique de types généraux de système propulsif pour l'étude des forces de torsion et de poussée en jeu, ainsi que des défauts d'alignement dynamiques et statiques.

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SUMMARY

A number of successful full scale tests of icebreaker propulsion systems have been completed in recent years. The principal motivation for much of this recent work has been to provide an adequate experimental basis for the development and validation of numerical modeling techniques for predicting the performance of alternative shafting and bearing arrangements. Such models should not only provide appropriate quantitative information concerning the loads experienced by key system components such as shaft bearings, but should also reproduce the overall qualitative behavior of the system observed at full scale. The main objective of this project was to develop a software package to access the full scale data and execute numerical models, for the design and evaluation of ice class shafting and propeller systems.

A software package, called the **Shaft Modeling Tool Kit**, was developed for this purpose. It is the first available comprehensive software package for the analysis of ice class shafting and propeller systems. The suite of programs (written for IBM PC/AT compatibles) in the **Shaft Modeling Tool Kit** provide the following:

- Access to key Full Scale Data from several ice class vessels
- Tabular Displays of the Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR) for Powering, Shafting, and Propellers
- Analytical Modeling of generalized shafting and propeller systems for Torsion, Thrust, and Alignment (Dynamic and Static)

The program is entirely menu-driven, that is, the user selects the program function to be performed from lists, or menus. Items are selected from menus with the mouse. By moving the mouse, the user places an arrow on the monitor over the item in the menu he wishes to select and then presses the mouse button.

The program is currently being used by designers of ice class shafting and propeller systems. It has proven to be an extremely useful design tool by providing the user with the calculated dynamic response of an ice class shafting and propeller system in a matter of minutes. High quality graphic functions enable the user to evaluate the calculated response of the model by comparing the time history results to measured full scale data.

Recommendations for further development include the following:

- Add capability for inclusion of Non linear spring (bearing) elements.
- Add capability to Input forces from the prime mover and gear box (if applicable).
- Produce a suite of ice induced propeller torque, thrust, and bending time histories by execution of the model for a series of shafting and propeller systems.
- Include other aspects of regulations
- Recommend revisions to regulations based upon analysis of full scale data and execution of shafting and propeller models.

SOMMAIRE

Un progiciel a été mis au point afin d'analyser les systèmes propulsifs (arbre et hélices) renforcés pour la navigation dans les glaces. Il s'agit du Shaft Modeling Tool Kit (fonctionnant sur ordinateurs IBM PC/AT et compatibles) offrant les fonctions suivantes:

- traitement des données en vraie grandeur concernant plusieurs navires de cote arctique pour en extraire les paramètres clés;
- affichage, sous forme de tableau, des valeurs spécifiées dans le Règlement sur la prévention de la pollution des eaux arctiques par les navires, à l'égard des systèmes propulsifs (machines, ligne d'arbre et hélices);
- modélisation analytique de types généraux de systèmes propulsifs pour l'étude des forces de torsion et de poussée en jeu ainsi que des défauts d'alignement dynamiques et statiques.

Le programme est entièrement piloté par menus, ce qui signifie que l'utilisateur sélectionne la fonction de programme à exécuter à partir de listes, ou menus. Dans ces derniers, les articles sont sélectionnés à l'aide d'une souris. A l'aide de celle-ci, l'utilisateur déplace le curseur à l'écran et le positionne sur l'article désiré, et appuie alors sur le bouton.

Le programme est actuellement utilisé par des concepteurs de systèmes propulsifs. Il s'est avéré un outil de conception extrêmement utile puisqu'il permet à l'utilisateur de chiffrer, en quelques minutes, la réponse dynamique d'un système propulsif. Des fonctions graphiques de qualité supérieure permettent à l'tilisateur d'évaluer les résultats fournis par le modèle, en comparant les graphiques force-temps aux données en vraie grandeur.

Les recommandations concernant la poursuite des travaux de développement comprenaient entre autres:

- l'ajout d'une fonction permettant de prendre en considération les éléments d'appui non linéaires (paliers);
- l'ajout d'une fonction afin de tenir compte des forces exercées par les moteurs et les réducteurs (le cas échéant);
- la production d'un ensemble de graphiques sur l'évolution dans le temps des forces de torsion, de poussée et de flexion attribuables aux glaces, en procédant à des simulations intéressant une série de systèmes propulsifs différents;
- l'ajout de fonction de traitement concernant d'autres aspects de la réglementation;
- la proposition de modifications à la réglementation en fonction de l'analyse des données en vraie grandeur et des résultats de la modélisation des systèmes propulsifs.

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1. INTRODUCTION

During the past fifteen years Canada has achieved a position of world leadership in many aspects of the technology of arctic marine transportation. This has come about both through the efforts of private industry and through the systematic technical programs of Government of Canada agencies such as the Canadian Coast Guard and the Transportation Development Centre of Transport Canada. The private companies involved have been concerned primarily with the technical and economic problems posed by the transportation and operational requirements of Arctic resource development. Government agencies have been primarily concerned with providing the regulatory framework for industrial operations in the Arctic and with the problems of operating and maintaining a growing fleet of ice capable shipping employed in carrying out Government missions.

A prominent feature of the Canadian approach in this field has been the emphasis upon the acquisition of full scale engineering data and the use of operational experience to guide and inform the technology development process. This is natural considering that, in Canada, our environment presents a particularly wide range of sea ice conditions and we have had the opportunity to operate a wide range of differing ship sizes and designs in these conditions. Since the early seventies Canadian agencies and companies have either conducted or participated in more than forty major programmes of full scale experimentation with ice going ships.

The reliability of the propulsion system is one of the most important considerations in the design and operation of ice going shipping, for two reasons. Firstly, the propellers, shafting, shaft seals and shaft bearings are amongst the most vulnerable parts of an ice transiting ship. They are exposed to repeated, very high amplitude loads and vibration levels. Secondly, the failure of this equipment has a great impact on the ability of the ship to perform its mission and hence upon the overall economics of its operation.

The design practice for ice-going propulsion machinery has evolved much as the design criteria for ice breaking hulls has; experience of damage and failure of system components in early designs has led to progressive increases in strength requirements, typically expressed as an ice strengthening factor applied to the strength requirements for clear water designs. Over the past several decades this approach has been successful in substantially controlling the incidence of catastrophic failure and in reducing progressive deterioration of system performance to manageable levels.

However, the large body of empirical design rules developed in response to early system failures does not necessarily provide adequate guidance for the specification of entirely new types of propulsors which take advantage of new technology. Such developments as ice going controllable pitch propellers, ducted propellers for enhanced thrust and new types of prime movers with different control and torque delivery characteristics all offer attractive advantages to the system designer, but may give rise to entirely new problems not anticipated in classical design practice. What is needed in such circumstances is a reliable, qualitative model of how of ice-propeller interaction loads arise and are propagated in a generalized propulsion system.

Full Scale Testing

Of the large number of full scale trials programmes carried out in this country, most have included the measurement of basic propulsion system responses to ice loads. Measurements of transient shaft torque, thrust and propeller speed data, together with relevant prime mover and control signals have been obtained for a variety of ships, propulsion system types and ice conditions.

Since 1980 this data base has been substantially augmented through increasingly detailed full scale investigations focused on particular aspects of the propulsion-ice interaction process. The two most extensive programmes of propulsion machinery measurements have been the 1984 M.V. Robert Lemeur Propeller Blade Load Measurement Programme and the 1986 M.V. Kalvik Propulsion System Full Scale Test Programme both of which were cooperative programmes involving TDC and private industry interests. Both programmes represent unique sources of full scale data on a world wide basis. The only other vessels to have been the subject of comparable types of full scale propulsion system measurements have been the USCGC Polar class icebreakers and a small Finnish harbour tug.

The M.V. Robert Lemeur Propeller Blade Load Programme has provided the first qualitative as well as quantitative picture of how a ducted c.p. propeller is loaded during ice operations. The data helps us to understand the different geometrical loading conditions that can arise at the propeller itself and to see the relative frequency and severity of each type.

The M.V. Kalvik Propulsion System Full Scale Test Programme provides the first complete picture of all modes of shafting and bearing response to propeller-ice loading. For the first time the bending response of a heavy shafting system, as well as its axial and torsional responses, has been measured during severe ice-propeller interaction. In addition, both the circumferential and longitudinal transient load distributions within the rubber stave stern tube bearings were measured, together with the transverse movement of the shafting at the stern tube seal and the complete response of the hull girder and foundation structure in way of the shaft line. The result is the most detailed picture so far obtained of the complete response of a shafting system to propeller ice impact loads.

Modeling

The principal motivation for much of this recent work has been to provide an adequate experimental basis for the development and validation of numerical modeling techniques for predicting the performance of alternative shafting and bearing arrangements. Such models should not only provide appropriate quantitative information concerning the loads experienced by key system components such as shaft bearings, but should also reproduce the overall qualitative behavior of the system observed at full scale.

The **Shaft Modeling Tool Kit** is the first available comprehensive software package for the analysis of ice class shafting and propeller systems. The suite of programs (written for IBM PC/AT compatibles) in the **Shaft Modeling Tool Kit** provide the following:

- Access to key ***Full Scale Data*** from several ice class vessels
- Tabular Displays of the ***CASPPR Regulations*** for Powering, Shafting, and Propellers
- Analytical ***Modeling*** of generalized shafting and propeller systems for Torsion, Thrust, and Alignment (Dynamic and Static)

This report describes the structure of the program and how to use it. The model structure and the solution techniques used are also presented.

2.0 Program Description

2.1 Hardware Requirements

The following are the minimum hardware requirements:

1. IBM PC/AT Compatible Computer c/w 640 kBytes of RAM
2. EGA Graphics Card
3. EGA Colour Monitor
4. 1.2 MByte Floppy Disk Drive
5. 40 MByte Hard Disk Drive
6. Microsoft or equivalent Mouse
7. IBM Dot Matrix Printer or equivalent
8. 80287 or 80387 math co-processor

2.2 Program Organization

Figure 2.2.1 illustrates the overall program structure flow chart. The following sections describe the program organization of each component or element.

Database

Figure 2.2.2 illustrates the structure of the database section of the program. The database section of the program provides quick access to data pertaining to several ice-class vessels, including component specifications and data from full scale propulsion system monitoring. The full scale data included was selected after an extensive review of the many documents produced and data collected from tests conducted between 1977 and 1987. The data selected represents typical and extreme events for each vessel, including ice-propeller interaction such as milling, blockage in the case of nozzled propellers, and short duration impacts. Data is presented in tables and time history plots. The user of the program can view the specifications of vessel components; display a synopsis of the full scale tests including the environmental conditions and test specifics; and view the time history of any signal collected during one of the tests.

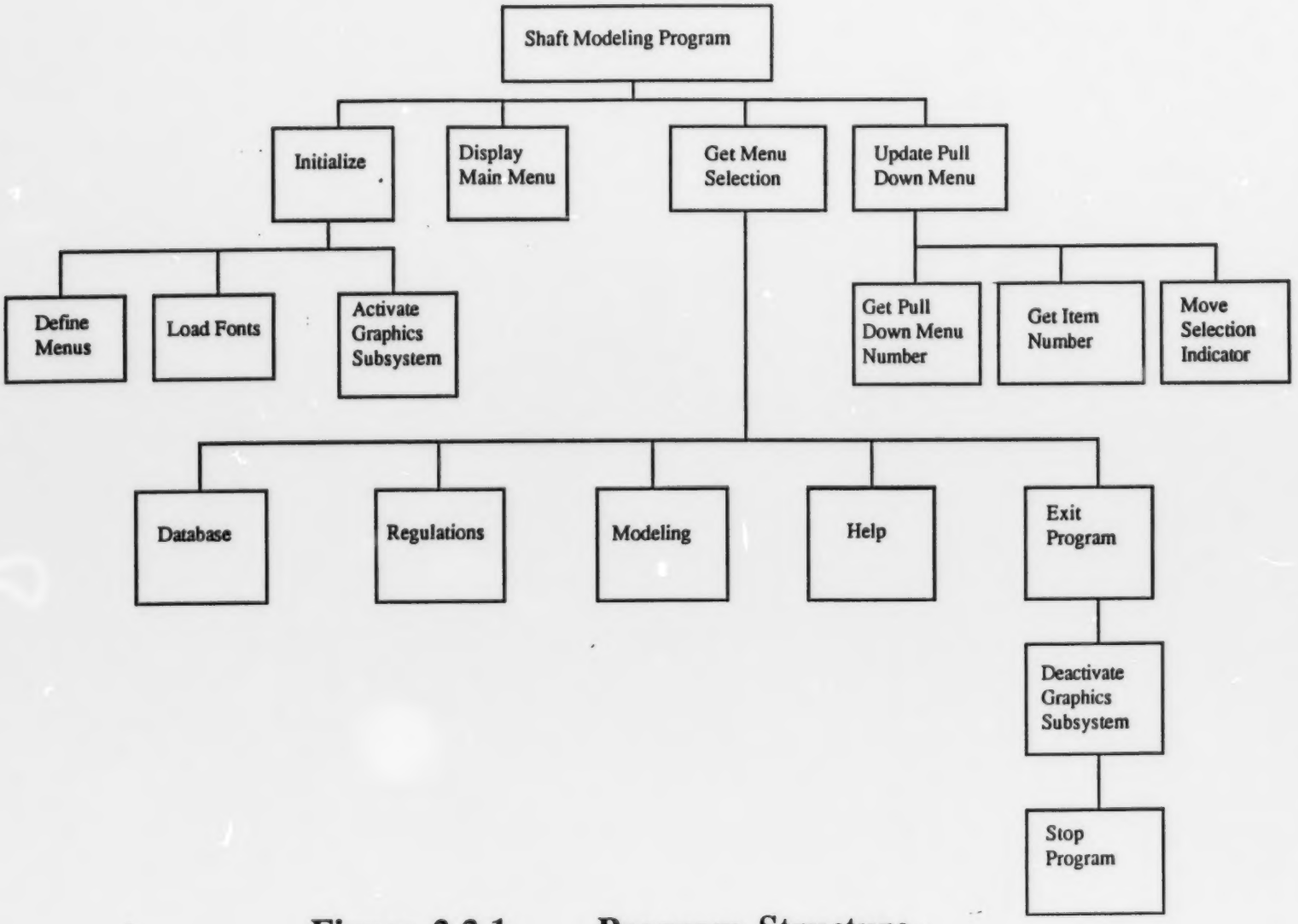


Figure 2.2.1 Program Structure

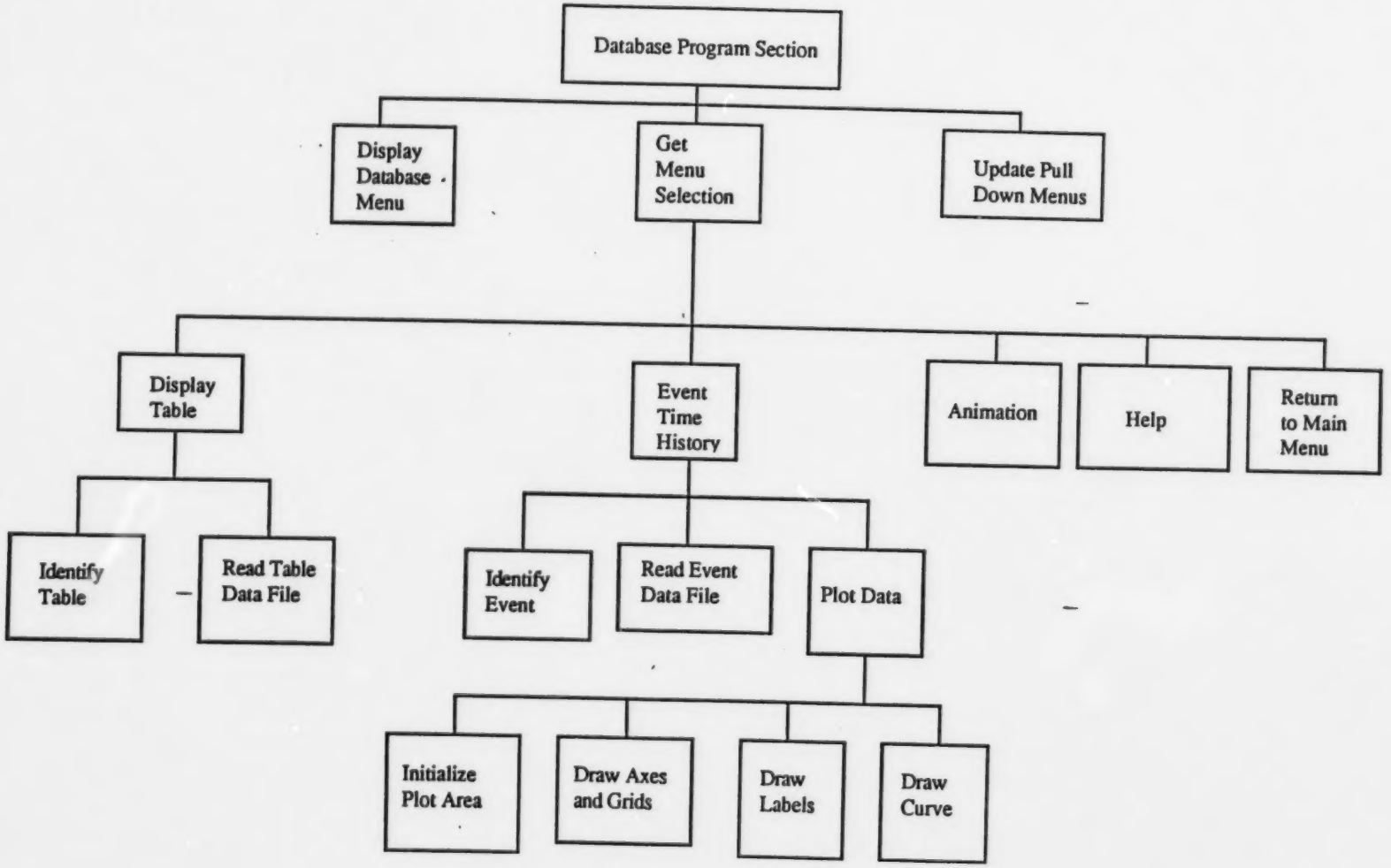


Figure 2.2.2 Structure of the Data Base Section

Modeling

Figure 2.2.3 illustrates the structure of the modeling section of the program. Table 2.2.1 and 2.2.2 list the model input and output parameters, respectively. The modeling section of the program provides the user with a tool to predict the dynamic response of an arbitrary shafting system due to ice-propeller interaction. Analysis options are available to calculate Torsional (Torque Model), Axial (Thrust Model), and Transverse (Alignment) dynamic response. A static alignment analysis option is also provided. Components such as the propeller, shafting, flywheel, oil distribution box and gearbox can be changed and specified by the user. Ice forces on the propeller used in the calculations can be specified or calculated using state of the art ice-propeller interaction algorithms.

Regulations

The regulations section of the program provides the user with a description of the current CASPPR pertaining to the powering and machinery requirements. This data is useful for comparing data in the full scale data base and modeling results with the expected loads and component specifications as described in the regulations.

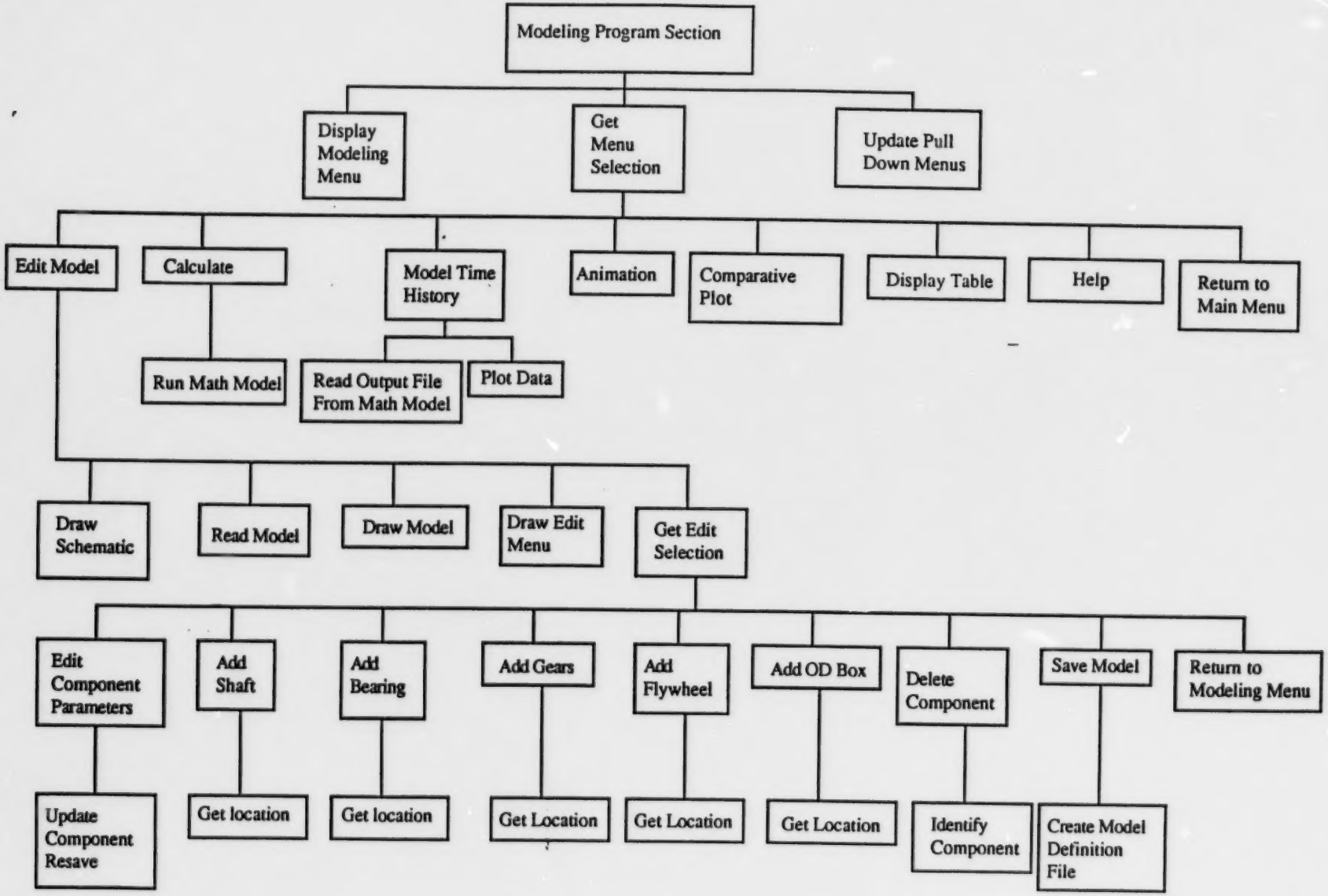


Figure 2.2.3 Structure of the Modeling Section

Table 2.2.1 Model Input Parameters

Shaft Elements	**Units**
Outside Diameter	meters
Inside Diameter	meters
Length	meters
Modulus of Elasticity (E)	GPa.
Torsional Modulus	GPa.
Mass Density	kg/m^3

Propeller	**Units**
Type	1: Nozzled, 2: Open
Diameter	meters
Hub Diameter	meters
Expanded Area Ratio	/
RPM	/
Blade Width	meters
Blade Tip Thickness	mm
Blade Pitch	degrees
Polar Moment of Inertia	kgm^2
Mass	kg
Damping	Torsion: kgm^2/sec Thrust: kg/sec Alignment: kg/sec
Number of Blades	/
Blade Root Thickness	mm
CASPPR Class	/
Ship Speed	m/sec

Bearings	**Units**	
Type	1: Thrust 2: Vertical 3: Torsion 4: Bending	
Stiffness	Torsion: Thrust: Bending: Vertical:	Nm/rad N/m Nm/rad N/m
Offset	mm	

(Only Static Alignment Analysis, Vertical Bearing)

Concentrated Masses and Inertias	**Units** (for all Types)	
Electric Motors		
Gear Wheel	Torsional Inertia:	kgm^2
Flywheel	Mass:	kg
Couplings		
Oil Distribution Boxes		

Integration Parameters	**Units**
Time	seconds
Time Step	seconds
Damping Coefficient Alpha	/
Damping Coefficient Beta	/

Table 2.2.2 Model Output Parameters

Output Parameter	Model
Torque at each beam element	Torque Model
Thrust at each beam element	Thrust Model
Reaction of each bearing	All Models
Displacement at each node	Dynamic Alignment Model
Propeller Force Time History	All Models

2.3 Using the Program

Menus

The program is entirely menu-driven, that is, the user selects the program function to be performed from lists, or menus. The menus are organized hierarchically, such that selecting an item from one menu may enable other menus. There are three types of menus, the major difference between them being the way they are displayed: Top-line menus are displayed in a bar across the top of the monitor; Pull-down menus are displayed directly under a top-line menu option when that option is selected; and Pop-up menus appear at various locations on the monitor depending on which function has been selected.

Items are selected from menus with the mouse. By moving the mouse, the user places an arrow on the monitor over the item in the menu he wishes to select and then presses the mouse button. The item is selected when the button is released. When the button is depressed, the item under the arrow is highlighted, thus, the user can ensure selection of the desired item by depressing the button, moving the mouse until the desired option is highlighted and then releasing the button. If the button is released outside all the menus, that is, without any item highlighted, no selection is made.

Pull-down menus are only enabled while the mouse button is depressed. To enable a pull-down menu, the user selects an item from a top-line menu using the method described above, but without releasing the button. A pull-down menu appears below the selected top-line menu item and the user then selects an item from the pull-down menu using the method described.

Selecting an item from a menu will do one of three things: enable other menus; set a parameter for a program function; or initiate a function. If a parameter is set, a colored box appears beside the parameter when the menu is displayed.

Keyboard Input

Besides interacting with the program via the mouse, the user must sometimes use the keyboard. The keyboard is used, for the most part, to enter new parameter values and to supply model names. When keyboard input is required, a box is displayed with a prompt indicating what input is expected.

Instruction Bar

A bar across the bottom of the monitor contains instructions and explanations at various points in the program to assist the user.

2.4 Plotting Options

Time history plots may be drawn representing data in the database or output from the modeling functions. Displays can also be produced showing any two available waveforms. In all cases where waveforms are displayed, a menu of editing options is present to the right of the actual graph.

Scaling Options

When a time history plot is drawn, the program determines default minimum and maximum values for both the x and y axis. These values may be adjusted by the user in either of two ways: by moving a cursor to the new value with the mouse; or by entering the desired value with the keyboard. To move the cursor to a new value, move the arrow on the monitor with the mouse to the appropriate arrow box (increase or decrease) for the parameter to change (ie. xmin, xmax, ymin or ymax) and depress the button. Release the button when the cursor reaches the desired value. To enter the new value from the keyboard, select the box labelled 'SET' for the particular parameter. A prompt box appears and the new value can be entered. Select the box 'REDRAW' after new scale values have been input to see the new plot.

Selecting the 'RESET' box for one of the four parameters sets the value for that parameter back to the default. All four values can be set to their respective defaults by selecting the large 'RESET' box near the bottom of the menu.

Getting a Printout

A printout of the current time history display can be obtained by selecting the 'HARDCOPY' box.

2.5 Database Functions

Database Time Histories

In the database section of the program, the 'Vessels' pull-down menu lists the ships for which full scale data is present in the database. The 'Events' pull-down menu indicates the test conditions under which the data was collected; and the 'Signals' pull-down menu indicates which sensors were monitored during a particular test. The 'Events' menu changes depending on which vessel has been selected in the 'Vessels' menu. Similarly, the 'Signals' menu is dependent on the 'Events' menu and changes accordingly.

To produce a time history display of full scale data from the database, the user must identify the data by:

1. Selecting the appropriate vessel from the 'Vessels' menu.
2. Selecting the event from the 'Events' menu
3. Selecting the signal from the 'Signals' menu.
4. Selecting 'Time History' from the 'Actions' menu.

The display produced is a 2 axis plot with the x axis in time (seconds) and the y axis in engineering units (ie. kN, mm, kNm).

Refer to the help section' Plotting Options' for information on changing the x and y scales and on producing a hard copy of the plot.

Bearing Reactions

Full scale bearing reaction data collected during trials conducted on the M.V. Kalvik may be animated. To view the animation:

1. Select 'M.V.Kalvik" from the 'Vessels' Menu.
2. Select an event from the 'Events' menu.
3. Select 'Bearing Reactions' from the 'Actions' menu.

A display is produced with a scaled plotting area superimposed over a model diagram of the ship's propulsion system. During animation, a vertical bar is drawn at the location of each bearing along the shafts indicating the reaction at each time step. An option menu is enabled which allows the user to increase or decrease the speed of the animation; step through the animation by the indicated time step; produce a hard copy of the current display; and to abort the animation prematurely.

NOTE: This function is available for M.V. Kalvik data only.

Database Tabular Data

The database includes vessel specifications and particulars of the tests during which the waveform data was collected. This information can be displayed or printed in tabular format. The information that is displayed depends on the items selected from the 'Vessels', 'Tables' and 'Components' pull-down menus.

Vessel Specifications

Particulars of each vessel's hull, propeller, shafting, gears and bearing can be displayed by:

1. Selecting the appropriate vessel from the 'Vessels' menu.
2. Selecting 'Specifications' from the 'Tables' menu.
3. Selecting the appropriate component from the 'Components' menu.
4. Selecting 'Display Table' from the 'Actions' menu.

Test and Event Data

Summaries of ice and environmental data and statistical data (maximum, minimum and mean values) for selected full scale waveforms can be produced by:

1. Selecting the appropriate vessel from the 'Vessels' menu.
2. Selecting 'Statistics' (for statistical data) or 'Ice Conditions' (for environmental data) from the 'Tables' menu.
3. Selecting 'Display Table' from the 'Actions' menu.

Hard Copies

To get a printout of a table, follow the same steps as above but select 'Print Table' from the 'Tables' menu instead of 'Display Table'.

Comparison Plot

This item can be selected from either the modeling or database 'Actions' menu. It is used to compare two time histories from any of the available waveforms, either from the full scale database or from the modeling analysis results. The feature is useful for comparing the calculated results from a model with corresponding full scale data, by displaying them simultaneously.

Selection of waveforms to plot is made through a series of pop-up menus. The user chooses first between 'Database' and 'Modeling' to indicate the origin of the data. If 'Database' is selected, subsequent menus ask the user to select a vessel, an event and a signal; if 'Modeling' is selected, subsequent menus ask the user to select a response type and a position (ie. node, shaft or bearing number). The user can select 'Cancel' at any menu to back up to the previous one. The process is repeated for the second waveform.

Once the waveforms are drawn, the same editing options are available as for a single waveform display as described under 'Plotting Options' in the Help menu. To enable the scaling options for one of the waveforms, it is necessary to select one waveform by clicking on the small square to the right of the waveform.

2.6 Modeling Functions

Edit Model

To make use of the Finite Element Modeling routines, the user must create and/or edit a model of a propulsion system. Model definitions are stored in files on the hard disk and may be recalled at any time. Five models are pre-defined representing the following vessels: the M.V. Kalvik, Robert Lemeur, the CCGS Louis S. St.-Laurent, the CCGS Pierre Radisson, the M.V. Arctic, and the USCGC Polar Sea.

To edit a model definition, the user does the following:

1. Selects the model from the' Models' pull-down menu.

2. Selects 'Edit Model' from the 'Actions' menu

The 'Models' menu lists the five models above and two further options: 'New Model' and 'Stored Model'. The former permits the user to create a definition beginning with a basic model; the latter permits the user to recall a model which he has created earlier. If 'Stored Model' is enabled, a prompt box appears when 'Edit Model' is selected asking the user to input the name of the model he wishes to edit.

Editing a Model

After 'Edit Model' has been selected, the model diagram is displayed with a schematic drawing of the vessel propulsion system, where available, and an editing menu. Selecting the appropriate item from the menu permits the user to add or delete a component (shaft, bearing, gearbox, flywheel or oil distribution box); save any changes made to the model definition file; or quit editing without saving any changes.

Adding a Component

To add a component to the model definition, the user selects the appropriate item from the menu depending on the component type he wishes to add. He then indicates where to insert the new component by clicking the mouse on the shaft immediately to the left of the position for the new component. A box appears showing default values for the required parameters for the selected component. The user can change any of the parameter values by clicking on the value to change and entering the new value from the keyboard. After making any required changes, the user selects 'Save Changes' and the component is added to the model definition. The model is also redrawn to include the new component.

If, after selecting one of the add component items from the menu, the user decides he does not wish to add a component, he may simply move the mouse so it is not touching a component and click the button.

Deleting a Component

To delete a component from the model definition, the user selects 'Delete Component' from the menu and then clicks the mouse on the component to delete. The component is removed from the model definition and the model is redrawn with the component removed.

If, after selecting 'Delete Component', the user decides he does not wish to delete any component, he may simply move the mouse so it is not touching a component and click the button.

Changing Parameter Values

The user can change any component parameter value of the model for sensitivity and parametric variation analyses. To edit the parameters of a particular component in the model, the user moves the mouse to the appropriate component and clicks the button. A box appears at the center of the screen indicating the parameters for the component and the current values. To change a value, select the parameter with the mouse and enter the new value at the prompt box with the keyboard. When all changes have been made, select 'Save Changes' to update the model definition, or 'Cancel' to ignore any changes made.

Edit Integration Parameters

When 'Edit Integration parameters' is selected from the 'Actions' menu, a window appears at the center of the screen containing the parameters and their current values. Select values to change with the mouse and enter new values from the keyboard when the prompt box appears. Select 'Save Changes' to store new values or 'Cancel' to retain the initial values when the window was opened.

The Integration Parameters are:

1. Time Step (seconds):

   Time interval in which shafting response is calculated. This value should be approximately 0.05 times the inverse of the expected frequency of vibration.

   Example: Expected Frequency = 10 Hz
   Time step = (0.05)/(10) = 0.005 seconds

   Note: If the time step is not small enough to resolve the frequency desired, the resulting waveform will appear to have damping, even if zero damping is selected.

2. Total Time (seconds):

   Total time for shafting response calculation. This value should be approximately 100-300 times the time step. The calculation time is proportional to the ratio of the total time to the time step.

3. Damping Coefficients Alpha and Beta:

   From Raleigh Damping (See Section 3.2.3 Integration Technique)

Edit Programmed Forces

Selecting 'Edit Programmed Forces' from the 'Sections' menu permits the user to edit the forcing function parameters. Values to change are selected with the mouse and stored by selecting 'Save changes'. Selecting 'Cancel' causes the initial values before change to be retained.

The parameters used in the calculations depend on the Ice Force type selected from the 'Ice Force' menu and the Model Type selected from the 'Analysis' menu. The following tables indicate which parameters are used for each Force type/Model with a brief description of the analysis.

Ice Force Type	Description	Parameters
Single Impact	One triangular shaped force impulse	Start Time, Duration
Milling	Triangular shaped force impulses	Impact Space, Duration
Ramp Force	Linear increase of force to constant value	Ramp Time, Start Time
Sine Wave	Sine wave forcing function	Frequency
Blockage	Oscillating Triangular Forces	Impact Space, Duration

Model Type	Description	Parameter
Torque	Ice torque on propeller	Ice Propeller Torque (kNm)
Thrust	Thrust on propeller	Ice Propeller Thrust (kn)
Alignment (Ice Bending)	Bending moment on propeller	ice Propeller Bending (kNm)
(Vertical Ice)	In plane force on propeller	Ice Propeller Vertical Force (kN)

Calculate

Selection of 'Calculate' from the 'Actions' menu initiates the modeling calculations. The following parameters are input to the modeling routines:

1. The definition of the model currently selected in the 'Models' menu.
2. The ice force type currently selected in the 'Ice Force' menu.
3. The ice strength currently selected in the 'Ice Type' menu.
4. The model type currently selected in the 'Analysis' menu.
5. The current values of the integration parameters as set by selecting 'Edit Integration Parameters' from the 'Actions' menu.
6. The current values of the programmed forces parameters as set by selecting 'Edit Programmed Forces' from the 'Actions' menu.

The modeling routines calculate the dynamic response of the model of the shafting system by the Wilson-theta direct integration method or the static bearing reactions of a model depending on the model type selected in the 'Analysis' menu. An icon in the shape of a sand glass time piece is displayed on the screen while the calculations take place and all interaction with the program is suspended.

Response Time History

Selection of this item from the 'Actions' menu presents the user with a pop-up menu from which calculated response curves of the model may be selected for time history plots. The following table indicates what response curves are available for plotting depending on the model type selected in the 'Analysis' menu:

Model Type	Type of Response	Curves to Plot
Torque and Thrust	Shaft Displacement	Response at each Node
Torque	Shaft Torque	Response of each Shaft
Thrust	Shaft Thrust	Response of each Shaft
Alignment	Bearing Reaction	Response of each Bearing

The user uses the mouse to select the type of response to plot and then the node, shaft or bearing number. These numbers may be changed by clicking on the current value and entering a new one in the prompt box. Selecting the 'Plot' box causes the time history to be drawn; selecting the 'Cancel' box removes the pop-up menu without drawing a plot.

The node, shaft and bearing numbers can be determined in the 'Edit Model' section of the program. Clicking on a shaft or bearing opens a window containing the parameter values for that component. The title of the window includes the element number. The node number on the left side of a shaft element is equal to the shaft element number; the node number on the right side of a shaft element is equal to 1 plus the shaft element number.

Force Time History

This item is selected from the 'Actions' menu in order to plot a time history of the input ice force on the propeller. If the 'Alignment' model type was run, the force plotted is the vertical ice force only; the bending moment force on the propeller is not plotted. However, the shape of the bending moment waveform is the same as the vertical ice force and magnitude is equal to that input or that calculated from the propeller model. The magnitude of the bending moment is displayed when editing the programmed forces.

Animation

The animation feature of the program, selected from the 'Actions" menu, is used to analyze the distribution of the response forces throughout the model. For example, if a torsional model is run, the magnitude of the torque response of each shaft element in the model is shown in animation as a vertical bar for each point in time. Therefore, the user can observe the decrease in torsional vibration from the propeller to the forward end of the shaftline.

An option menu is enabled which allows the user to increase or decrease the speed of the animation; step through the animation by the indicated time step; produce a hard copy of the current display; and to abort the animation prematurely.

Comparison Plot

This item can be selected from either the modeling or database 'Actions' menu. It is used to compare two time histories from any of the available waveforms, either from the full scale database or from the modeling analysis results. The feature is useful for comparing the calculated results from a model with corresponding full scale data, by displaying them simultaneously.

Selection of waveforms to plot is made through a series of pop-up menus. The user chooses first between 'Database' and Modeling' to indicate the origin of the data. If 'Database' was selected, subsequent menus ask the user to select a vessel, an event and a signal; if 'modeling' is selected, subsequent menus ask the user to select a response type and position (ie. node, shaft or bearing number). The user can select 'Cancel' at any menu to back up to the previous one. The process is repeated for the second waveform.

Once the waveforms are drawn, the same editing options are available as for a single waveform display as described under 'Plotting Options' in the help menu. To enable the scaling options for one of the waveforms, it is necessary to select one waveform by clicking on the small square to the right of the waveform.

Print Input Parameters

Select this item from the 'Actions' menu to print a hardcopy of the current inputs to the modeling routines: model name, date and time model was last modified, the model type from the 'Analysis' menu, the force type form the 'Ice Force' menu, the ice strength from the 'Ice Type' menu, and the current values of the Integration and forcing Function parameters.

Print Model Specifications

Select this item from the 'Actions' menu to print a hard copy or the values of all parameters of all components in the currently selected model. The date and time the model was last modified is also printed.

Print Model Diagram

Select this item from the 'Actions' menu to print a hard copy of the model diagram and the propulsion system schematic diagram where one is available.

2.7 Regulation Functions

The Arctic Shipping Pollution Prevention Regulations are used in this section of the program. The regulations section of the program allows the user to input the specifications of the powering and propulsion system components for either an existing ship or a ship in the design stage. The minimum requirements as specified in the regulations are displayed as well as the specified design parameters and the ratio of the design specifications to the rules.

3.0 Development of Model Structure and Solution Techniques

3.1 Structure of Shafting Model

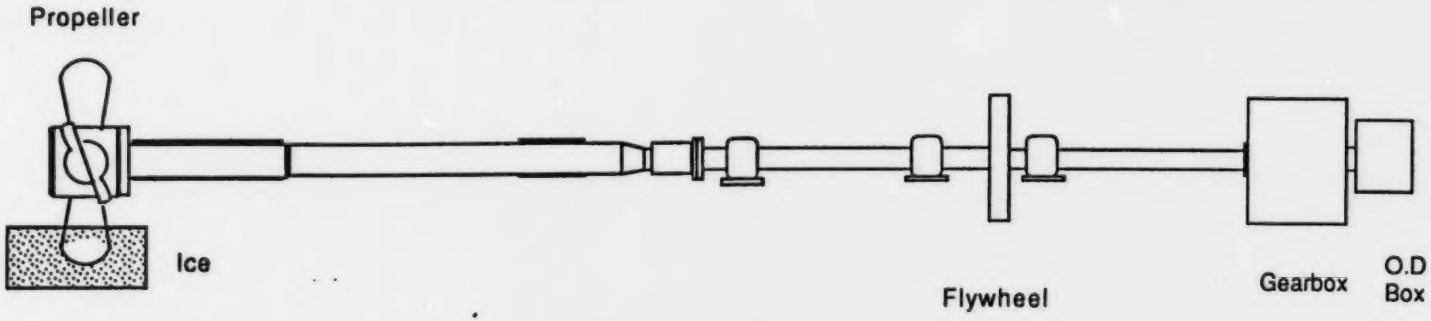
The development of an effective model for the dynamic response of ice class shafting systems requires a knowledge of the following:

1. Full scale data
2. Structural dynamics
3. Numerical analysis
4. Computer applications

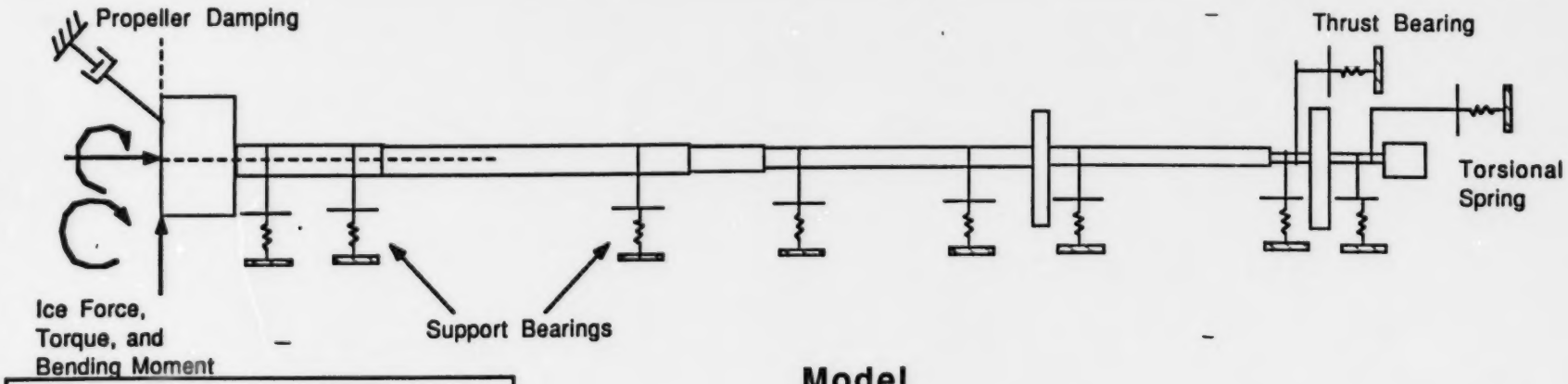
Full scale data provides qualitative and quantitative information on the dynamic response of real systems, such as: measured shaft torque and thrust, bearing stiffness and damping. The development of accurate and efficient structural elements requires a modern background in structural dynamics. The efficiency of a computer modeling program depends largely on the numerical techniques employed and on their effective computer implementation. With regard to programming techniques, an optimum allocation of high and low speed storage is necessary.

The developed shaft model is composed of a linear system of continuous beam elements with concentrated springs (bearings), damping (propeller damping), and masses (electric motors, flywheels, etc.). An illustration of the M.V. Kalvik shaftline along with the model representation is shown in Figure 3.1.1. This type of modeling representation of the shafting allows for parametric variation of model components in terms familiar to marine engineers. Each beam element has a node at both ends with up to six degrees of freedom per node. Concentrated springs (bearings), torsional inertias, and masses can be applied at any node in the model. Ice forces on the propeller are included by applying an input force waveform on the node representing the propeller (extreme left node).

Three types of dynamic response calculations can be done: Thrust, Torque, and Alignment. The shafting model must be composed of at least one shaft, one bearing, and a propeller, and the type and number of bearings must be chosen such that rigid body motion be inhibited.



Schematic



Model

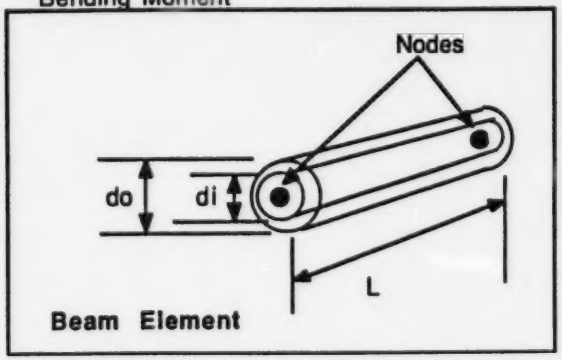


Figure 3.1.1 Modeling of the M.V. Kalvik Shaft Line

3.2 Integration Technique

The nodal point equilibrium equations for a linear system of structural elements , such as this shaft model, yield a set of linear equations of the following form:

$$[M]\,[\ddot{y}] + [C]\,[\dot{y}] + [k]\,[y] = [F]$$

where:

- [M] - Mass Matrix of beam element
- [C] - Damping Matrix of beam element
- [k] - Stiffness Matrix of beam element
- [F] - Forcing Function Matrix (Ice Forces on Propeller)
- $[\ddot{y}]$ - nodal acceleration matrix
- $[\dot{y}]$ - nodal velocity matrix
- [y] - nodal displacement matrix

The structural matrices (for entire model) are formed by direct addition of the element matrices: for example

$$[k] = \Sigma\,[k_m]$$

where k_m is the stiffness matrix of the m'th element. Although k_m is formally the same order as k, only those terms in k_m which pertain to the element degrees of freedom are nonzero. The addition of the element matrices can therefore be performed by using the element matrices in compact form together with identification arrays which relate element to structure degrees of freedom.

Based upon previous modeling experience and full scale data analysis, it was determined that the modeling solution technique must conform to the following criteria:

1. Fast calculation time
2. Proven reliability
3. Ability to solve response for complex input forcing functions (ice force on propeller)
4. Capability for inclusion of lumped damping, stiffness, and mass

5. Ability to expand to more complex modeling for future development, without extensive modification to software code. Additions may include:
    - ice interaction algorithm (input force is dependent upon the response of the shaftline)
    - non-linear spring elements
6. Solve response in the form of a time history
7. Unconditionally stable

The two most common solution techniques are those of mode superposition and the direct integration method. Direct integration is equivalent to a mode superposition analysis in which all the eigenvalues and vectors have been calculated and the uncoupled equations are integrated with a common time step Δt. The integration can only be accurate for those modes for which Δt is smaller than a certain fraction of the period T (usually 0.01 times T). Using the Wilson-θ method the integration errors effectively "filter" the high mode response (ie. for which $\Delta t/T$ is large) out of the solution. This filtering is due to amplitude decay observed in the numerical solution when $\Delta t/T$ is large. The effective filtering of those high frequency response from the solution may be beneficial. Integration accuracy cannot be obtained in the response of the modes for which $\Delta t/T$ is large and the filtering process allows one to obtain a total system solution in which the low mode response is accurately observed. It is therefore noted that the direct integration technique is quite equivalent to a mode superposition analysis, in which only the lowest modes of the system, but a sufficient number to take proper account of the applied loading, are considered. The exact number of modes effectively included in the analysis depends on the time step size Δt and the distribution of the vibration periods.

The advantages of the direct integration method over the mode superposition method is that it is more effective when the response is required over relatively few time steps, such as in shock problems (propeller-ice impacts). Also the direct integration technique can accommodate non-linear spring elements and the ability to develop ice-interaction algorithms, without extensive software code revision. Therefore, the Wilson-θ method of direct integration was chosen as it satisfied all of the criteria specified.

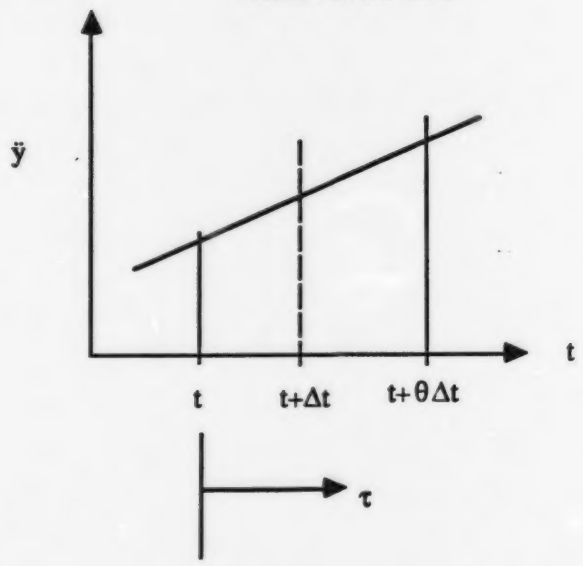
The Wilson-θ method is essentially an extension of the linear acceleration method in which the acceleration during any one time step is assumed to vary linearly. It assumes that the acceleration is linear over a range of θ times the solution time step. Paz, 1985 [1] developed the equations of motion using the Wilson-θ method by adopting an incremental load approach. The original development by Wilson was for the total load at each step, but both methods give the same final equation. The development of the equations of motions using the total load at each time step is described in the following section as well as the equations including Rayleigh damping.

Equilibrium Equations: $[M]\,[\ddot{y}] + [C]\,[\dot{y}] + [k]\,[y] = [F]$

where:

- [M] - Mass Matrix of beam element
- [C] - Damping Matrix of beam element
- [k] - Stiffness Matrix of beam element
- [F] - Forcing Function Matrix (Ice Forces on Propeller)
- $[\ddot{y}]$ - nodal acceleration matrix
- $[\dot{y}]$ - nodal velocity matrix
- [y] - nodal displacement matrix

Linear Acceleration



Solve for acceleration, velocity, and displacement, at time = t+Δt in term of values at time t.

At any time t

Acceleration:

$$\ddot{y}_{t+\tau} = \ddot{y}_t + (\tau/(\theta\Delta t))(\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t) \qquad 1$$

(ie. Linear Acceleration)

Velocity:

Integrate Acceleration $\int_0^{\tau} d\tau$ to get velocity

$$\int_0^{\tau} \ddot{y}_{t+\tau}\, d\tau = \int_0^{\tau} \ddot{y}_t\, d\tau + \int_0^{\tau} (\tau/(\theta\Delta t)(\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t) d\tau$$

$$\dot{y}_{t+\tau} = \dot{y}_t + (\ddot{y}_t)(\tau) + (\tau^2/(2\theta\Delta t))(\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t) \qquad 2$$

Displacement:

Integrate Velocity $\int_0^{\tau} d\tau$ to get displacement

$$\int_0^{\tau} \dot{y}_{t+\tau}\, d\tau = \int_0^{\tau} \dot{y}_t\, d\tau + \int_0^{\tau} (\ddot{y}_t)\, \tau\, d\tau \int_0^{\tau} (\tau^2/(2\theta\Delta t))\, (\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t)\, d\tau$$

$$y_{t+\tau} = y_t + (\dot{y}_t)(\tau) + (\ddot{y}_t)(\tau^2/(2)) + (\tau^3/(6\theta\Delta t))(\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t) \qquad 3$$

Rearranging Terms:

$$\ddot{y}_{t+\theta\Delta t} = (6\theta\Delta t/(\tau^3))\, (y_{t+\tau} - y_t - (\dot{y}_t)(\tau) - (\tau^2/(2))\ddot{y}_t) + \ddot{y}_t$$

At Time $\tau = \theta\Delta t$

$$\ddot{y}_{t+\theta\Delta t} = (6/(\theta\Delta t)^2)(y_{t+\theta\Delta t} - y_t) - (6/(\theta\Delta t))\ \dot{y}_t - 2\ddot{y}_t \qquad 4$$

At Time $\tau = \theta\Delta t$ equation **2** yields:

$$\dot{y}_{t+\theta\Delta t} = \dot{y}_t + (\ddot{y}_t)(\theta\Delta t) + (\theta\Delta t)^2/(2\theta\Delta t))(\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t)$$

$$\dot{y}_{t+\theta\Delta t} = \dot{y}_t + (\ddot{y}_t)(\theta\Delta t) + (\theta\Delta t/2)[(6/(\theta\Delta t)^2)(y_{t+\theta\Delta t} - y_t) - (6/(\theta\Delta t)(\ \dot{y}_t) - 2\ddot{y}_t - \ddot{y}_t)]$$

$$\dot{y}_{t+\theta\Delta t} = \dot{y}_t + (\ddot{y}_t)(\theta\Delta t) + (3/(\theta\Delta t))\ (y_{t+\theta\Delta t} - y_t) - 3\ \dot{y}_t - (\theta\Delta t/(2))\ (3\ddot{y}_t)$$

$$\dot{y}_{t+\theta\Delta t} = (3/(\theta\Delta t))\ (y_{t+\theta\Delta t} - y_t) - 2\ \dot{y}_t - (\theta\Delta t/(2))(\ddot{y}_t) \qquad 5$$

Equations of motion of an n-degree of freedom system with viscous damping and arbitrary excitation R (t+$\theta\Delta$t) can be presented in matrix form by:

$$M\ddot{y}_{t+\theta\Delta t} + C\,\dot{y}_{t+\theta\Delta t} + Ky_{t+\theta\Delta t} = R_{t+\theta\Delta t} \qquad 6$$

Substitute equations **4** and **5** into **6** yields:

$$M\ [6/(\theta\Delta t)^2(y_{t+\theta\Delta t} - y_t) - (6/(\theta\Delta t))\ y_t - 2\ddot{y}_t\ ]$$

$$+ C\ [(3/(\theta\Delta t))(y_{t+\theta\Delta t} - y_t) - 2\ \dot{y}_t - (\theta\Delta t/(2)\ddot{y}_t]$$

$$+K\ [\ y_{t+\theta\Delta t}\ ]$$

$$= R_{t+\theta\Delta t} = R_t + (\theta\Delta t)(R_{t+\Delta t} - R_t)/\Delta t$$

$$= R_t + \theta\ (R_{t+\Delta t} - R_t)$$

Rearranging Terms:

$$M[6/(\theta\Delta t)^2(y_{t+\theta\Delta t})] + C[(3/(\theta\Delta t))(y_{t+\theta\Delta t})] + K[y_{t+\theta\Delta t}]$$

$$= R_t + (\theta)(R_{t+\theta t} - R_t) + M[6/(\theta\Delta t)^2 y_t + (6/(\theta\Delta t))\dot{y}_t + 2y_t]$$

$$+ C[(3/(\theta\Delta t) y_t + 2\dot{y}_t + (\theta\Delta t/(2))\ddot{y}_t] \qquad 7$$

OR

$$(\underline{K})(y_{t+\theta\Delta t}) = \underline{R}$$

Where:

$$\underline{K} = K + (6/(\theta\Delta t)^2)(M) + (3/(\theta\Delta t))\ C$$

$$\underline{R} = R_t + \theta\Delta R + M[(6/(\theta\Delta t)^2) y_t + (6/(\theta\Delta t))\dot{y}_t + 2\ddot{y}_t]$$

$$+ C[(3/(\theta\Delta t)) y_t + 2\dot{y}_t + (\theta\Delta t/(2))\ddot{y}_t]$$

$\underline{K}$ = effective stiffness matrix

$\underline{R}$ = effective load vector

Substituting equation **4** into **1** for $\tau = \Delta t$

$$\ddot{y}_{t+\Delta t} = \ddot{y}_t + (\Delta t/(\theta\Delta t))[(6/(\theta\Delta t)^2)(y_{t+\theta\Delta t} - y_t) - (6/(\theta\Delta t))\ \dot{y}_t - 2\ddot{y}_t - \ddot{y}_t]$$

$$\ddot{y}_{t+\Delta t} = (6/\theta(\theta\Delta t)^2)[y_{t+\theta\Delta t} - y_t] - (6/(\theta^2\Delta t))\dot{y}_t + (1 - (3/\theta))\ddot{y}_t] \qquad 8$$

At $\tau = \Delta t$ equation **2** yields:

$$\dot{y}_{t+\Delta t} = \dot{y}_t + (\ddot{y}_t)(\Delta t) + (\Delta t^2/(2\theta\Delta t))(\ddot{y}_{t+\theta\Delta t} - \ddot{y}_t) \qquad 9$$

Rearranging terms in equation **1** and setting $\tau = \Delta t$

$$\ddot{y}_{t+\theta\Delta t} = (\ddot{y}_{t+\Delta t})(\theta\Delta t/(\Delta t)) - (\theta\Delta t/(\Delta t))(\ddot{y}_t) + \ddot{y}_t \qquad 10$$

Substituting **10** into **9** at $\tau = \Delta t$ yields:

$$\dot{y}_{t+\Delta t} = \dot{y}_t + (\ddot{y}_t)(\Delta t) + (\Delta t/(2\theta))[(\ddot{y}_{t+\Delta t})(\theta) - \theta\,\ddot{y}_t + \ddot{y}_t - \ddot{y}_t]$$

$$\dot{y}_{t+\Delta t} = \dot{y}_t + (\Delta t/2)(\ddot{y}_{t+\Delta t} + \ddot{y}_t) \qquad 11$$

Substituting equation **10** into **3** at $\tau = \Delta t$ yields:

$$y_{t+\Delta t} = y_t + (\dot{y}_t)(\Delta t) + (\ddot{y}_t)(\Delta t^2/2) + (\Delta t^3/(6\theta\Delta t))[(\ddot{y}_{t+\Delta t})(\theta) - (\theta)\,\ddot{y}_t + \ddot{y}_t - \ddot{y}_t]$$

$$y_{t+\Delta t} = y_t + (\dot{y}_t)(\Delta t) + (\Delta t^2/6)(\ddot{y}_{t+\Delta t} + 2\ddot{y}_t) \qquad 12$$

3.3 Damping

Raleigh damping: $C=\alpha[M]+\beta[K]$ where: α and β are constants

The constants α and β can be chosen to best fit the damping characteristics of system. Typically a sensitivity analysis is done to determine what changes in α and β have on the response of the shafting system.

Using Raleigh damping the modal damping ratio becomes: $\xi_i = \alpha/(2\omega_i) + \beta\omega_i/2$

where: ξ_i= modal damping ratio
ω_i= natural frequency of the i'th modal response

If α is set to zero (0) then the damping becomes structural and $\beta=2\xi_i/\omega_i$

for critical damping: $\xi_i = 1$
$\beta = 2/\omega_i$

3.4 Static Alignment

The solutions to the static vertical bearing reactions for a shaft model are solved from the static equilibrium matrix equation:

$$[F]=[k][y]$$

where:

[F] = Force matrix
[k] = Stiffness matrix
[y] = Nodal displacement matrix (displacement of each node)

The static alignment algorithm performs the following:

1. Calculates the stiffness matrix as is done in the dynamic analysis
2. Calculates the force matrix based upon:
   - the shaft weight
   - the force to move the shaft to the specified offset at each bearing
3. Solves the nodal displacement matrix for the calculated force and stiffness matrices
4. Calculates the vertical force, F_v, in each shaft element, by multiplying the calculated nodal displacement by the appropriate stiffness at each node.
5. Calculates the bearing reactions from the nodal static equilibrium conditions ($\Sigma F_v=0$).

3.5 Flexibility of Hull

To investigate the effect bending of the hull has on the static bearing reactions an offset can be input at a bearing location and the static alignment calculation can be repeated. The resulting reactions can be compared to the reactions calculated from the original offsets. The difference between the two sets of reactions is a result of a hull deflection corresponding to the specified bearing offset. However, full scale tests on the M.V. Kalvik concluded that the dynamic bearing reactions are insignificant when the vessel is ramming a ridged ice feature causing the hull to bend significantly. The dynamic bearing reactions are most significant when ice-propeller interaction is occurring, not when the vessel is flexing due to ramming.

3.6 Ice-Propeller Interaction Algorithms

Arctic Research and Development Limited (ARAD) was subcontracted to do a literature review and evaluation of the existing ice-propeller interaction models. Three models were selected, from a total of eleven models reviewed, to be implemented into the modeling program:

1. Jagodkin (1963)
2. Edwards (1978)
3. Laskow (1986)

Jagodkin Model

This model was developed in 1963 as a first rational attempt at calculating the shaft torque due to the propeller interacting with ice. This model is based upon the theory of cutting tools. The icebreaking propeller blade is idealized as a wedge cutting into the ice block. Ice failure is represented as crushing and shearing combined. The model has been developed to apply to fixed pitch open propellers and calibrated to a diesel electric drive system with a 3.5 m diameter propeller. It is recommended to use this model to determine benchmark values. The output of the model is the ice induced propeller shaft torque.

Edwards Model

This model was developed in 1978 to determine the ice forces acting on open fixed pitch large diameter propellers, for the Arctic Pilot Project LNG carrier. It is based upon the concept of a perfectly rigid tool cutting into a perfectly brittle material. Material fails in crushing and shear. The model is similar to the Jagodkin model but with two additional improvements: blade shadowing effect, and simultaneous blade immersion in ice. The model does not account for shrouded propellers, hydrodynamic loads, or load shedding due to a decrease in pitch of a controllable pitch propeller; however, it is recommended to be used as a working predictive tool. The output from the model is the ice induced shaft torque, thrust, and bending, for one blade and multi-blade passes in ice.

Laskow Model

This model was developed as a result of the full scale trials of the icebreaking supply vessel M.V. Robert Lemeur, with a shrouded controllable pitch propeller. Two expressions were developed: one for the single blade impact on a block of ice, giving the maximum blade force, and the second one calculating the maximum ice induced shaft torque during ice milling. The model algorithm is based upon the full scale data only.

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